

# Lyman- $\alpha$ Emitters at Redshift $z=5.7$

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## ABSTRACT

Lyman- $\alpha$  galaxies at high redshifts offer a powerful probe of both the formation of galaxies and the reionization of the intergalactic medium. Lyman- $\alpha$  line emission is an efficient tool for identifying young galaxies at high redshift, because it is strong in systems with young stars and little or no dust — properties expected in galaxies undergoing their first burst of star-formation. Lyman- $\alpha$  galaxies also provide a robust test of the reionization epoch that is independent of Gunn-Peterson trough observations in quasar spectra and is better able to distinguish line center optical depths  $\tau \sim 5$  from  $\tau \sim 10^5$ . This is because neutral gas scatters Lyman- $\alpha$  photons, dramatically “blurring” images of Lyman- $\alpha$  galaxies embedded in a neutral intergalactic medium and rendering them undetectable.

We present a photometrically selected sample of redshift  $z \approx 5.7$  Lyman- $\alpha$  emitters derived from the Large Area Lyman Alpha survey. The presence of these low-luminosity Lyman- $\alpha$  sources immediately implies that the reionization redshift  $z_r > 5.7$ . Comparing these objects to our earlier  $z \approx 4.5$  sample, we find that the number of  $z \approx 5.7$  emitters at fixed line luminosity marginally exceeds the no-evolution expectation, but falls well short of published model predictions. The equivalent width distribution is similar at the two redshifts. The large equivalent widths of the Lyman- $\alpha$  line indicate young galaxies undergoing their first star formation.

*Subject headings:* galaxies: general — galaxies: evolution — galaxies: formation — galaxies: statistics — cosmology: observations — early universe

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## 1. Introduction

Recent discoveries of high redshift objects are steadily taking us closer to determining the epoch of galaxy formation (Dey et al. 1998; Spinrad et al. 1998; Weyman et al. 1998; Hu, McMahon, & Cowie 1999; van Breugel et al. 1999; Fan et al. 2001), if such a well-defined time period exists. Observations of neutral hydrogen absorption troughs (the Gunn-Peterson effect) seem to indicate that intergalactic hydrogen was reionized and hence that the ionizing UV “turned on” between  $z \approx 6.3$  and  $z \approx 5.7$  (Becker et al. 2001, Djorgovski et al. 2001).

A more direct probe of galaxy formation is to determine the number counts and redshift evolution of nascent galaxies. The Large Area Lyman Alpha (LALA) survey (Rhoads et al. 2000) has been designed and executed to detect large enough samples of high-redshift emitters to be statistically useful. Strong Lyman- $\alpha$  emission, shown by large equivalent widths in the line, indicates that these are young galaxies (Malhotra et al. 2001). Since large scale structure can influence galaxy counts even at high redshifts (Steidel et al. 1998, Adelberger et al. 1998), large area surveys are vital to study redshift evolution. Narrow-band surveys maximize sensitivity and solid angle, and allow us to push for higher redshift objects by designing narrow-bands to avoid bright sky lines.

Lyman- $\alpha$  galaxies also offer a particularly direct and robust test of the reionization epoch (Haiman & Spaans 1999). Before reionization, Lyman- $\alpha$  emitting galaxies of normal luminosity are effectively hidden from view by the scattering “fog” of the neutral IGM (Miralda-Escudé 1998; Rybicki & Loeb 1999). Thus, the reionization redshift should be marked by a sharp decrease in the number counts of faint Lyman- $\alpha$  emitters. This test is independent of the Gunn-Peterson trough observations in quasar spectra. Moreover, the Gunn-Peterson test has difficulty distinguishing opaque but modest optical depths  $\tau \sim 5$  from the much larger obscuration  $\tau \sim 10^5$  expected in a neutral IGM. Lyman- $\alpha$  galaxy counts can resolve this ambiguity. The red wing of the Lyman- $\alpha$  line from a star forming galaxy sees only the red damping wing of intergalactic Lyman- $\alpha$  absorption, and Lyman- $\alpha$  galaxies therefore remain detectable up to line-center optical depths  $\tau \sim 10^4$ .

In this paper we report on a population of candidate  $z \approx 5.7$  Lyman- $\alpha$  emitters discovered in the second phase of LALA survey and compare their properties to the  $z=4.5$  sample (Rhoads et al. 2001). Section 2 describes our observations and data reduction. In section 3 we present the candidates and their properties. Section 4 explores the implications of these discoveries for the epoch of galaxy formation.

## 2. Observations and data analysis

The Large Area Lyman Alpha survey began in spring 1998 as a narrowband search for  $z \approx 4.5$  Lyman- $\alpha$  emitting galaxies. The project was designed to exploit the high survey efficiency offered by the 36' field of the new CCD Mosaic Camera at the Kitt Peak National Observatory 4m Mayall Telescope. The core of the LALA survey is  $0.72^\circ$  in two fields centered at 14:25:57 +35:32 (2000.0) (the Boötes field) and 02:05:20 -04:55 (2000.0) (the Cetus field).

In April 2000, we extended the Boötes field survey to  $z = 5.7$  using custom-built narrowband filters having central wavelengths  $\lambda_c = 815, 823\text{nm}$ , full width at half maximum (FWHM) transmission  $7.5\text{nm}$ , and peak throughput  $\sim 90\%$ . The wavelengths were chosen to fall in a gap in the night sky emission line spectrum, thus minimizing sky noise. The filter bandpass deteriorated below these specifications outside a central circle of  $\sim 30'$  diameter. This resulted in substantially degraded throughput in the outer parts of our images, which we therefore excluded from our analysis.

The  $z = 5.7$  observing run was four nights, beginning with the night of 10–11 April 2000 (i.e., 2000 April 11 UT). The weather was generally clear. Photometric stability was checked by measuring the fluxes of selected stars on all science exposures. This showed  $< 11\%$  variation in throughput for the entire run, mostly due to airmass-dependent extinction.

We obtained 9.85 hours of data in 40 exposures through the 815 nm filter, and 9 hours in 36 exposures through the 823 nm filter. Exposures were spatially dithered with characteristic (RMS) offsets of  $\sim 50''$ . Seeing ranged from  $0.75''$  to  $2.25''$  (median  $0.93''$ ) in the 815 nm filter, and  $0.78''$  to  $1.25''$  (median  $1.01''$ ) in the 823 nm filter. Median narrowband sky brightnesses were  $27\mu\text{Jy arcsec}^{-2}$  at 815 nm and  $21\mu\text{Jy arcsec}^{-2}$  at 823 nm. We also obtained a deep (4 hour) image in a Sloan Digital Sky Survey  $z'$  filter during this run.

Data reduction was done in IRAF following the methods used for the  $z = 4.5$  sources (Rhoads et al 2000). The final stacks have point spread functions (PSF) with directly measured full widths at half maximum of  $0.88''$  (815nm) and  $0.97''$  (823nm). The PSF wings are higher than Gaussians of the same FWHM, since the images are sums of many frames with varying seeing. Catalogs were generated using SExtractor (Bertin & Arnouts 1996). Fluxes were measured in  $2.32''$  (9 pixel) diameter apertures, and colors were obtained using matched  $2.32''$  apertures in registered images. We also measured fluxes in earlier broad band images from the NOAO Deep Wide-Field Survey ( $B_W$ , R, and I bands) (Jannuzi & Dey 1999) and broad and narrow band images from previous LALA runs (V band and four  $\lambda \approx 6600\text{\AA}$  narrow bands).

We select  $z \approx 5.7$  candidates using the following criteria: (1) Secure detection in a

narrowband filter ( $> 5\sigma$ ). (2) A strong narrowband excess (narrow – broad color  $< -0.75$  magnitude, corresponding to a factor of  $\approx 2$  in flux density) that is securely measured (the flux density in the narrow band should exceed that in the broad band at the  $4\sigma$  level). (3) No flux at wavelengths shorter than the expected Lyman break wavelength (the object should remain undetected in  $B_W$  and V band fluxes at the  $2\sigma$  level or below). The first two criteria are designed to ensure that real emission line objects are selected, while the third rejects most low redshift emission line galaxies, using the blue bands as “veto” filters.

### 3. Survey Results

In total, 18 objects in the two filters (11 in the 815nm filter and 7 in the 823nm filter) passed all selection criteria and are considered good  $z \approx 5.7$  candidates. Photometric “mini-spectra” for these candidates are shown in figure 1.

Intergalactic hydrogen absorption is expected to attenuate the measured I band flux used for candidate selection. The formulation of Madau (1995) gives correction factors of 2 for  $z = 5.70$  and 2.2 for  $z = 5.77$ . We apply these corrections to the I band flux before calculating the equivalent widths of the emission lines from our broad and narrow band photometry. These corrections are comparable to the factor of 2 difference in flux density required for selection. We therefore apply another cut to our candidate lists, removing the five candidates whose observer frame equivalent widths fall below  $80\text{\AA}$  after the correction for hydrogen absorption. We expect these objects to be either high redshift *or* strong emission line objects, but they need not be both. Because intergalactic hydrogen absorption can also remove the bluest  $\sim 50\%$  of the Lyman- $\alpha$  line flux, our equivalent width corrections and the resulting candidate list cut are both quite conservative.

### 4. Discussion and Conclusions

We now turn to the implications of our survey for galaxy formation and cosmology. First, let us compare the statistics of  $z \approx 5.7$  sources to the  $z \approx 4.5$  Lyman- $\alpha$  emitters. There are 13 sources at  $z \approx 5.7$  and 156 at  $z \approx 4.5$ . However, a minority of our  $z \approx 4.5$  are bright enough to be detectable at  $z \approx 5.7$ .

Using a  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$  cosmology and accounting for the difference in solid angle between the two redshifts<sup>5</sup>, the comoving survey volume at  $z \approx 5.7$  is 31% that at  $z \approx 4.5$

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<sup>5</sup>The solid angle for the higher redshift is approximately a factor of two smaller due to the degradation

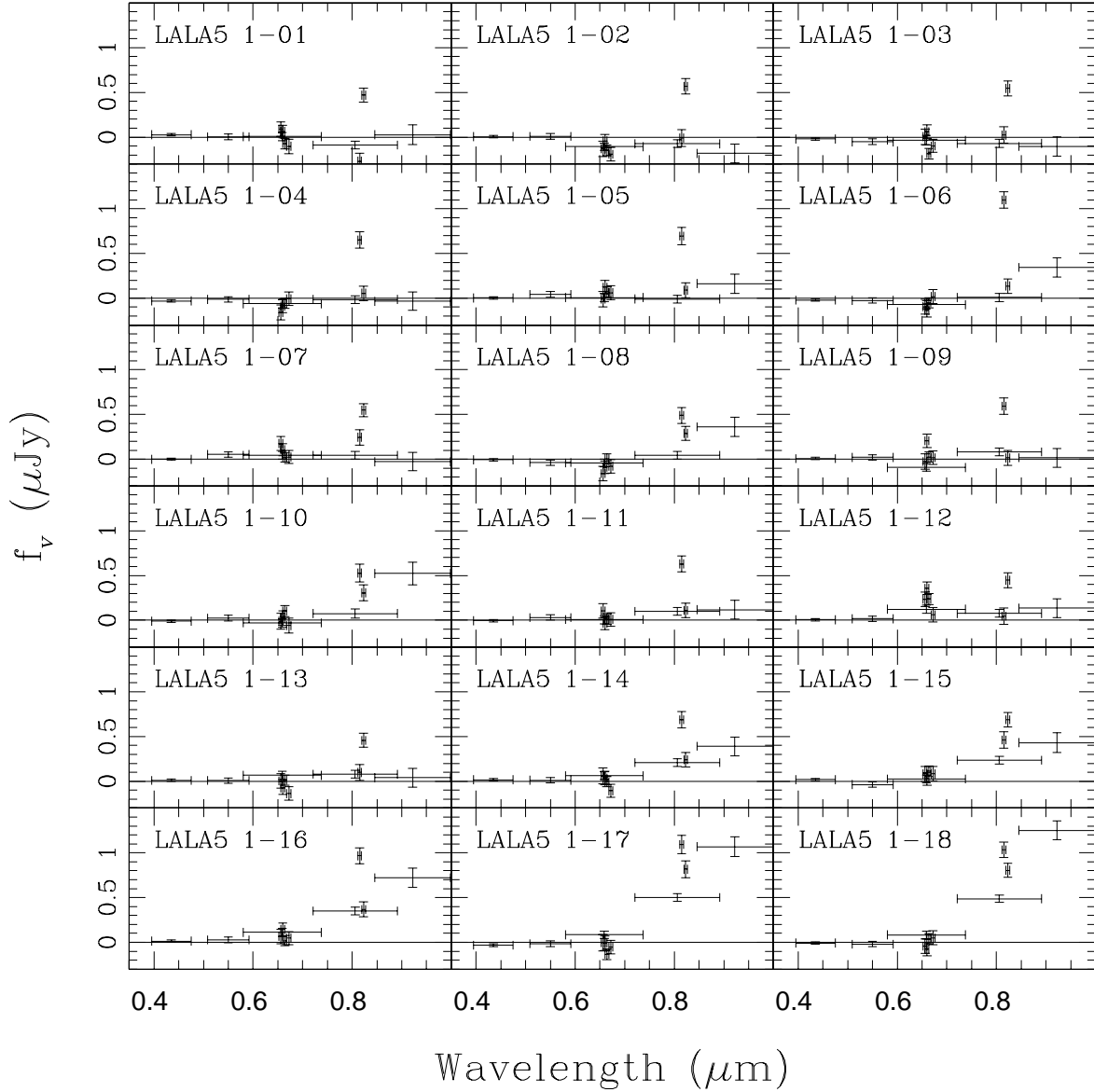


Fig. 1.— Photometric “mini-spectra” for the 18  $z \approx 5.7$  Lyman- $\alpha$  emitter candidates selected using the criteria discussed in section 2. All photometry was done through a  $2.32''$  diameter aperture centered on the object position derived from the narrowband filter containing the excess emission. The candidates are assigned ranked ID numbers based on the ratio of broad to narrow band flux density, which is a measure of emission line strength. This rank increases from left to right and from top to bottom. The last five candidates (LALA5 1-14 to LALA5 1-18) have observer frame equivalent widths below  $80\text{\AA}$  if we correct the continuum flux for the intergalactic hydrogen absorption expected at  $z \approx 5.7$ .

(16% in each filter). The  $5\sigma$  flux thresholds used to identify candidates at  $z \approx 5.7$  were  $0.455\mu\text{Jy}$  at 815nm and  $0.405\mu\text{Jy}$  at 823nm. The distance-corrected equivalent thresholds at  $z \approx 4.5$  will be larger by a factor of  $1.34^2 = 1.8$  for the above cosmology. There are then 15  $z \approx 4.5$  candidates that could be detected in our 815nm data, and 26 that could be detected in our 823nm data. Thus, based on the  $z \approx 4.5$  survey and a no-evolution assumption, we would expect to find 2.3 sources in the 815nm filter, and 4.1 in the 823nm filter. We actually identify 7 and 6 respectively.

This excess in the observed  $z \approx 5.7$  candidate counts is moderately significant (at the 99% level assuming Poisson source counts). The important difference is in the 815nm counts; the 823nm filter candidate counts are consistent with the naïve scaling from  $z \approx 4.5$ . We now examine several possible explanations for this effect.

First, Lyman- $\alpha$  emitters at  $z \approx 5.7$  may be more numerous and/or more luminous than those at  $z \approx 4.5$ . Such effects are reasonable: The Lyman- $\alpha$  line is resonantly scattered and can be strongly quenched by dust absorption. Since dust is formed from stellar nucleosynthesis products, we expect galaxies at earlier epochs to be (on average) less chemically evolved and less dusty. More luminous Lyman- $\alpha$  lines may be a natural byproduct, provided that the effects of chemical evolution are not overwhelmed by the trend of decreasing halo mass at higher redshift. Indeed, under the Lyman- $\alpha$  emitter population models of Haiman & Spaans (1999), evolutionary effects are so strong that the total surface density per unit redshift above a fixed line flux  $\sim 1.5 \times 10^{-17} \text{ erg cm}^{-2} \text{ s}^{-1}$  is approximately independent of redshift for  $3 \lesssim z \lesssim 6$ . Our results show a factor  $\sim 7$  decrease in the surface density of Lyman- $\alpha$  emitter candidates from  $z = 4.5$  to  $z = 5.7$  (in contrast to an expected factor  $< 2$  from the Haiman & Spaans models). The LALA data is thus more nearly consistent with a no-evolution model than with the baseline model from Haiman & Spaans (1999).

In addition, large scale structure can significantly affect the number counts of objects in single fields. Our  $36'$  field makes LALA results comparatively robust to such effects, but a factor of 2 difference in source density may still be consistent with cosmic variance.

Finally, our candidate sample will contain some residual contamination by foreground objects. The numbers of such objects should be comparatively small, given the high-redshift consistency checks described in sections 2 and 3. Foreground emission line galaxies are the most serious concern. Our primary defense against such galaxies is the requirement that a good candidate be undetected in deep broadband images with  $\lambda < (1 + z) \times 912\text{\AA}$ . This imposes an approximate minimum observer frame equivalent width for any interloper, which we estimate using the minimum narrow band flux  $5\sigma_n$  and maximum broad band flux

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of the bandpass near the filter edges; see section 2.

$2\sigma_b$ . (Here  $\sigma_n$  and  $\sigma_b$  are the photometric errors in flux density units for the narrow and broad blue filters.) The corresponding equivalent width is then  $\approx (f_n/f_b - 1) \times \Delta\lambda_n = [5\sigma_n/(2\sigma_b) - 1] \times \Delta\lambda_n \sim 1100\text{\AA}$ , where we assume that the line lies outside the broad band filter. The redshifts of likely foreground objects are relatively low ( $0.24 \lesssim z \lesssim 1.21$ ), and the corresponding emission frame equivalent widths therefore remain large ( $\gtrsim 500\text{\AA}$ ). While compact, narrow emission line galaxies can attain these equivalent widths, they are very rare (e.g., Hogg et al 1998).

Cool stars can also enter narrowband emission line samples because molecular absorption in their atmospheres produces spectral features with widths of a few nm and amplitudes several tens of percent. However, in the absence of true emission lines, cool stars will show detectable continuum at  $\gtrsim 1/2$  of the narrowband flux density, which is also expected to be quite red, so that our SDSS  $z'$  filter should clearly show such stars. Most of our candidates having strong  $z'$  detections were discarded from our sample by the last cut applied (see section 3). Only two of the 13 remaining sources, LALA5 1-08 and LALA5 1-10, have “minispectra” that plausibly resemble cool stars.

Because our narrow and broad band filters were obtained at different times, variable objects may also enter the sample at a low level. The relevant objects would have to have  $I \lesssim 24.3$  during the narrow band observations (2000 April 11–14 UT), and  $I > 25$  during the I band observation (1999 March 27 UT). (In fact, our requirement on the blue flux imposes additional limits.) The largest known source of such variable objects would be high redshift supernovae. However, these would show roughly equal brightness in both  $z \approx 5.7$  narrow bands and the SDSS  $z'$  image, since their characteristic variability timescale is several days. Again, only LALA5 1-08 and LALA5 1-10 are consistent with this expectation. Sources with faster variability, such as orphan GRB afterglows (Rhoads 1997), are very rare and we would expect  $\ll 1$  such source in our sample (e.g., Dalal et al 2001).

We compared the equivalent width distribution of the  $z = 4.5$  and  $5.7$  samples. Very low and high equivalent width objects are missing in  $z=5.7$  sample compared to  $z=4.5$  sample. Using a Kolmogorov-Smirnov test we find a 20% chance that the two samples are drawn from the same parent distribution. This test is only marginally conclusive, mostly because of the small number of  $z = 5.7$  objects. The consistency of the present samples is nonetheless further evidence that we are seeing the same class of object at  $z = 5.7$  as at  $z = 4.5$ .

In summary, we have a sample of 13  $z \approx 5.7$  Lyman- $\alpha$  emitting galaxy candidates. Only two of these have the apparent spectral energy distributions expected of stars or variable objects. The upper limits on blue flux rule out all but the highest equivalent width foreground sources, which are too rare to account for the entire sample. The equivalent width distributions are consistent at  $z \approx 5.7$  and  $4.5$ . Thus, the simplest explanation of the data

is that we are really seeing  $z \approx 5.7$  Lyman- $\alpha$  emitters.

We now draw one very robust and important conclusion from our sample. The epoch of reionization is a major landmark in the evolution of the universe. Recently, the Gunn-Peterson trough has been reported in spectra of two high redshift quasars: SDSSpJ 103027.10+052455.0 at  $z = 6.28$  (Becker et al 2001), and SDSS 1044-0125 at  $z = 5.73$  (Djorgovski et al 2001). These authors have interpreted their spectra as evidence that reionization was incomplete at these redshifts.

If the universe was neutral at redshift  $z_r < 5.67$ , Lyman- $\alpha$  photons from sources at higher redshift would be resonantly scattered in the neutral intergalactic medium (IGM). This effectively erases the Lyman- $\alpha$  line from view for a survey like LALA. Thus, our  $z \approx 5.7$  sample implies that the reionization redshift lies at  $z_r > 5.8$  along the line of sight to the LALA Boötes field. This argument relies merely on the *presence* of low-luminosity Lyman- $\alpha$  sources, and is independent of their exact number.

Two possible loopholes exist, but both are readily closed. First, in the absence of dust, the Lyman- $\alpha$  photons eventually scatter far enough into the line wing to propagate freely. However, this process spreads the line emission greatly in both area and frequency, resulting in a very large “photosphere” and a correspondingly low surface brightness (Loeb & Rybicki 1999). All of the sources reported in this paper are compact in the narrow band image (i.e., essentially unresolved at our resolution limit of  $\lesssim 1''$ ) and so morphologically inconsistent with a source embedded in a neutral IGM.

Second, a source with a sufficient ionizing flux will generate its own Stromgren sphere in the IGM. If this sphere is large enough, Lyman- $\alpha$  photons will redshift by  $\gtrsim 1000 \text{ km s}^{-1}$  before reaching the surrounding neutral gas, and will thus avoid resonant scattering. However, this effect requires sources either more luminous or older than typical LALA objects. We assume that a fraction  $f_{\text{esc}}$  of ionizing photons escape a galaxy to ionize its Stromgren sphere, and that  $2/3$  of the remainder result in Lyman- $\alpha$  photons, and that  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$ ,  $\Omega_\Lambda = 0.7$ , and  $\Omega_b = 0.05$ . We then require an ionized bubble radius  $r_s \gtrsim 1.2 \text{ Mpc}$ , which gives a Gunn-Peterson effect optical depth  $\tau \leq 1$  at emitted line center (see also Loeb & Rybicki 1999). Ignoring recombinations,  $r_s \gtrsim 1.2 \text{ Mpc}$  requires a source with  $L_{43} t_8 f_{\text{esc}} / (1 - f_{\text{esc}}) \gtrsim 5$ , where  $L_{Ly-\alpha} = 10^{43} L_{43} \text{ erg s}^{-1}$  and the source is  $10^8 t_8$  years old. LALA  $z \approx 5.7$  sources have  $L_{43} \approx 0.7$ . Their median rest frame equivalent width of  $\geq 80 \text{ \AA}$  requires  $f_{\text{esc}} \lesssim 0.2$  for any reasonable initial mass function<sup>6</sup>, unless  $t_8 \lesssim 0.3$  (Malhotra et al 2001; Kudritzki et al 1999). The age of the universe at  $z = 5.7$  requires  $t_8 < 10$ . Thus,

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<sup>6</sup>Continuous star formation with IMF slope  $\alpha = 2.35$  (i.e., Salpeter), upper mass cutoff  $120 M_\odot$ , metallicity  $Z = Z_\odot/20$ , and  $t_8 \gtrsim 0.3$  gives  $EW \approx 95(1 - f_{\text{esc}}) \text{ \AA}$ . Substantially larger EW requires  $\alpha \ll 2$ .



$L_{43}t_8f_{\text{esc}}/(1 - f_{\text{esc}}) \lesssim 2$ , and Lyman- $\alpha$  radiation from these sources would indeed suffer resonant scattering if the IGM were neutral.

We are thus confident that the compact, low-luminosity Lyman- $\alpha$  emitters we observe at  $z \approx 5.7$  are in a mostly ionized universe. This method offers a test for reionization independent of the spectroscopic search for Gunn-Peterson troughs. Moreover, it is better able to distinguish line center optical depths  $\tau \sim 10^5$  (indicating a neutral IGM) from much smaller but still essentially opaque optical depths  $\tau \sim 10$  (indicating Lyman- $\alpha$  forest absorption), because the Lyman- $\alpha$  forest will in general absorb only the blue side of the Lyman- $\alpha$  emission line, while a neutral IGM will absorb the entire line. For an intrinsic line width of  $\sim 100\Delta v_{100}\text{km s}^{-1}$ , we would still expect to see some Lyman- $\alpha$  flux through an IGM with a (homogeneously mixed) neutral fraction of  $\lesssim 0.1\Delta v_{100}((1+z)/6.7)^{-3/2}$ , while the Gunn-Peterson trough is optically thick ( $\tau \geq 5$ ) for a neutral fraction as small as  $\sim 4 \times 10^{-5}((1+z)/6.7)^{-3/2}$ .

To conclude, we have demonstrated that Lyman- $\alpha$  emitters are found at  $z \approx 5.7$  in densities comparable to those at  $z \approx 4.5$  at similar line luminosities. It follows that the reionization redshift was  $z_r > 5.8$ , at least along this line of sight. Tentatively, it appears that the Lyman- $\alpha$  source density at equal luminosity rises from  $z \approx 4.5$  to  $z \approx 5.7$ . We have also obtained pilot observations in a  $z \approx 6.6$  narrowband filter. This redshift lies beyond the recently reported Gunn-Peterson effect quasars, and will ultimately allow us to bracket the reionization epoch through Lyman- $\alpha$  source counts.

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